Catena 203 (2021) 105330

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Response of sediment discharge to soil erosion control in the middle reaches of the Yellow River

Yang Zhao [a], Chunhong Hu [b], Xiaoming Zhang [c,*], Xizhi Lv [d,*], Xiaolin Yin [e], Zhaoyan Wang [e]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, No. 20, Chegongzhuang West Road, Haidian District, Beijing 100048, China
[b] Academician of Chinese Academy of Engineering, China Institute of Water Resources and Hydropower Research, No. 20, Chegongzhuang West Road, Haidian District, Beijing 100048, China
[c] China Institute of Water Resources and Hydropower Research, No. 20, Chegongzhuang West Road, Haidian District, Beijing 100048, China
[d] Yellow River Institute of Hydraulic Research, No. 9, Huanghe Road, Jinshui District, Zhengzhou 450003, China
[e] China Institute of Water Resources and Hydropower Research, No. 20, Chegongzhuang West Road, Haidian District, Beijing 100048, China

ARTICLE INFO

Keywords:
Yellow River
Sediment source
Soil erosion control
Sediment reduction threshold

ABSTRACT

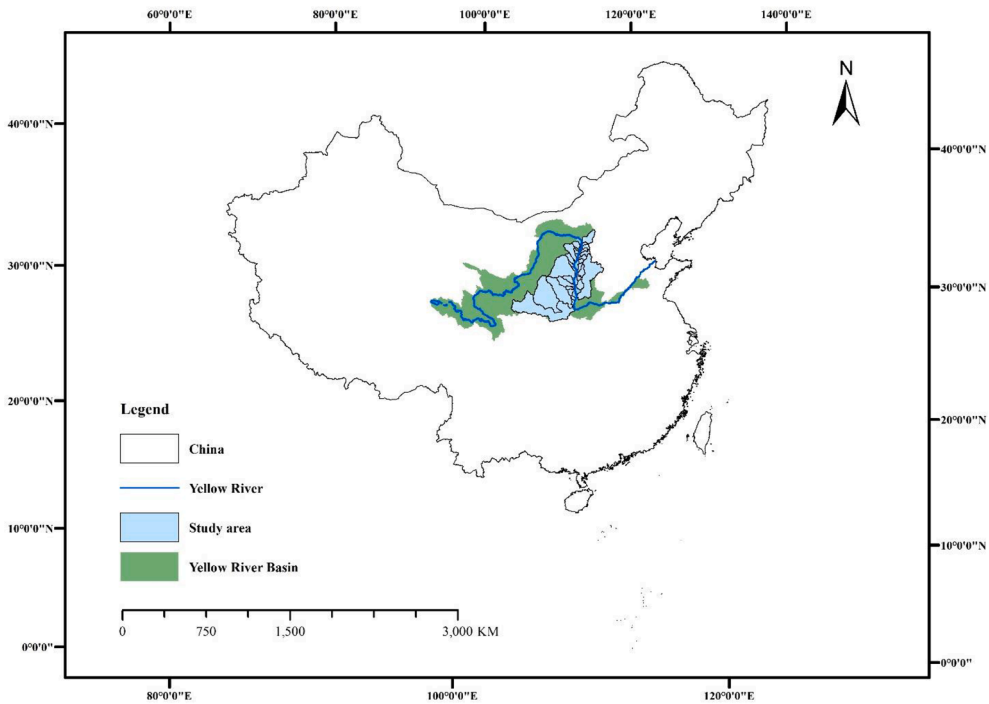
Under the background of large-scale, high-intensity, comprehensive soil erosion control, the sediment discharge of the Yellow River has undergone profound changes. The quantitative evaluation of the influences of soil and water conservation on sediment discharge is not only an inevitable requirement for the objective assessment of the ecological benefits of soil and water conservation projects, but it is also a prerequisite for gaining a scientific understanding of the causes of the drastic changes in the sediment discharge of the Yellow River. Taking the trunk stream in the Toudaoguai-Tongguan section of the middle reaches of the Yellow River and its 24 primary tributaries as the research objects, the Mann-Kendall test and the double mass curve were used to determine the spatial–temporal changes in the sediment discharge over the past 60 years. The results show the following. 1) The average annual sediment discharge in the Toudaoguai-Tongguan section decreased by 81.1% ($P < 0.001$) over the past 60 years, with a sudden decrease in 2000. 2) From 1956 to 2000, the Toudaoguai-Wubao section, the Wubao-Longmen section, and the Longmen-Tongguan section contributed 34.76%, 30.60%, and 34.64%, respectively, to the sediment discharge measured at Tongguan station. After 2000, the contribution rates were 11.17%, 38.93%, and 49.9%, respectively. 3) Compared with 1956–2000, the average annual sediment discharge of the primary tributaries during 2001–2016 decreased by an average of 85.61%. Marginal benefit analysis indicates that, once the degree of soil erosion control in the study area reached the critical value of 32%, the marginal sediment reduction benefits of the soil and water conservation measures approached 0. Once the degree of soil erosion control exceeded 50%, the sediment discharge in the river basin decreased to a low level. These research results provide a reference for future directions and priorities in soil erosion control planning and implementation on the Loess Plateau.

1. Introduction

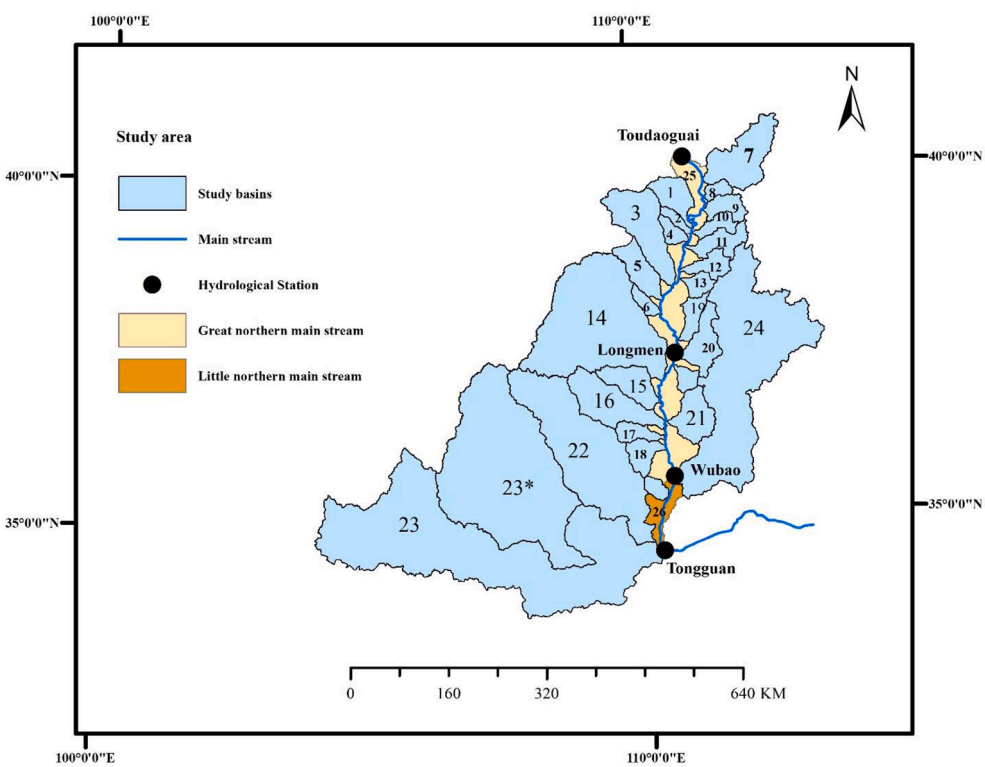
The flow and sediment processes of rivers play a vital role in maintaining the structure of a river's geomorphology and in maintaining ecosystem functions (Benn and Erskine, 1994). With global warming and increasingly intense human activities, the flow and sediment processes of rivers around the world have changed significantly (Hu and Chen, 2014). Walling and Fang (2003) pointed out that the average annual sediment discharge (~47%) of the world's major rivers, e.g., the Mississippi, the Indus, the Nile, and the Yangtze River, has significantly decreased. Li et al. (2020) showed that the annual sediment discharge (40%) of the major rivers of the world has experienced significant changes, with a significant decrease in the runoff and sediment discharge of the major rivers in Asia. The significant changes in the flow and sediment processes of rivers directly determine the layout of water conservancy projects along trunk streams and tributaries and the formulation and adjustment of river control strategies. Thus, the changes in the flow and sediment processes of rivers, especially the changes in the total amount and processes, have become the focus of worldwide attention (Liquete et al., 2009; Vaighan et al., 2017; Hu and

* Corresponding authors.
E-mail addresses: shuisha135@126.com (X. Zhang), nihulvxizhi@163.com (X. Lv).

https://doi.org/10.1016/j.catena.2021.105330
Received 11 April 2020; Received in revised form 19 February 2021; Accepted 20 March 2021
Available online 10 April 2021
0341-8162/© 2021 Elsevier B.V. All rights reserved.



(a)



(b)

Fig. 1. Location of the study area.

Zhang, 2020). The variation characteristics and attribute analysis of river sediment discharge under the influence of climate change and intensive human activities are the frontiers and popular topics of global studies of soil erosion and sediment (Brauer et al., 1999; Yang et al., 2017; Giardino et al., 2018).

Sediment discharge is an important indicator that objectively reflects the changes in the soil erosion intensity, which has made it an important aspect of soil erosion studies worldwide (Wu and Chen, 2012). As the region with the most severe soil erosion in the world, the Loess Plateau in the middle reaches of the Yellow River is the concentrated source area

Table 1
Overview of the trunk stream and main tributaries in the Toudaoguai-Tongguan section.

ID	Catchment	Area (10^4 km^2)	ID	Catchment	Area (10^4 km^2)	ID	Catchment	Area (10^4 km^2)
1	Huangfu	0.32	10	Zhujiachuan	0.29	19	Sanchuan	0.42
2	Qingshuichuan	0.088	11	Lanyi	0.22	20	Quchan	0.12
3	Kuye	0.87	12	Weifen	0.15	21	Xishui	0.43
4	Gushan	0.13	13	Qiushui	0.20	22	Beiluo	2.69
5	Tuwei	0.33	14	Wuding	3.03	23	Jinghe	4.54
6	Jialu	0.11	15	Qingjian	0.41	24	Weihe	6.25
7	Honghe	0.79	16	Yanhe	0.77	25	Fenhe	3.97
8	Pianguan	0.21	17	Fenchuan	0.18	26	Dabei main stream	1.88
9	Xianchuan	0.16	18	Shiwangchuan	0.24	27	Xiaobei main stream	0.3

of the sediment in the Yellow River (Fu, 1989). To accelerate the treatment of soil erosion on the Loess Plateau and to reduce the amount of sediment entering the Yellow River, since the 1970s, the government has implemented a series of ecological projects, such as the construction of silt dams, slope farmland improvement, and returning farmland to forests and grasslands, on the Loess Plateau (Zhang et al., 2017). After nearly 50 years of continuous management, the soil erosion management projects on the Loess Plateau have achieved remarkable results. As of 2018, the accumulated area involved in controlling the soil erosion reached 218,000 km^2, accounting for 48% of the total soil erosion area. Accordingly, the amount of sediment in the Yellow River has changed significantly. Taking Tongguan Hydrological Station on the trunk stream of the Yellow River as an example, during 2001–2018, the measured average annual sediment discharge decreased by 85% compared with 1919–1959 (Wang et al., 2020). It was not expected that the sediment discharge of the Yellow River changes would change so significantly. Determining the causes of the drastic changes in the water and sediment and analyzing the influence of large-scale soil erosion control on the reduction in the sediment discharge in the Yellow River Basin has become a topic that urgently needs to be investigated in order for the government to formulate future strategies in the Yellow River Basin and to determine the direction of soil erosion control on the Loess Plateau (Miao et al., 2010; Wang et al., 2016; Zhang et al., 2019).

The problem of sediment is the crux of the difficulties in the management of the Yellow River (Kang et al., 2010). Many studies have been conducted on the causes of the drastic reduction in the sediment discharge of typical tributaries of the Yellow River due to human activities based on observational data collected at the main hydrological stations on the main tributaries of the Yellow River (Miao et al., 2011; Zhao et al., 2018; Yao, 2019; Wang et al., 2020). These studies have yielded many results in terms of the marginal sediment reduction benefits of the soil and water conservation measures (Ren, 1994; Yao and Xu, 2013). However, we found that the research foundation is relatively weak when it comes to determining how the spatial–temporal changes in the sediment discharge of the Yellow River Basin respond to soil erosion control (Mu et al., 2014). The research objectives of these papers, i.e., determining the relationship between soil and water conservation projects and sediment discharge, have mostly focused on single-scale watersheds, while few multi-scale joint studies have been conducted (Wang et al., 2015). Although the effect of soil and water conservation measures on sediment reduction has been effectively verified in small-scale and medium-scale watersheds, few studies have included tributary watersheds of different sizes (Ni et al., 1997; Chen et al., 2019). There are two main reasons for the lack of studies that consider tributary watersheds of different sizes. First, the main sediment producing area in the Yellow River Basin covers nearly 300,000 km^2. With many tributaries that cover a wide range and involve multiple administrative areas, it is difficult to collect data from the various hydrological stations (Liu et al., 2016). In addition, the key areas for soil and water conservation often lack flow and sediment discharge data, which adds challenges to such studies. Second, due to the obvious scale effects on the benefits of the different soil and water conservation measures, it is difficult to directly extend the research results of small-scale and medium-scale watersheds to large-scale watersheds. This results in an unclear relationship between the soil and water conservation measures and the sediment discharge of the Yellow River and thus the absence of any consensus on the reasons for the drastic reduction in the sediment load of the Yellow River. To this end, relying on existing research projects, we systematically collected data on the soil and water conservation measures and sediment discharge for 24 of the primary tributaries in the main sediment producing areas in the middle reaches of the Yellow River. We used these data to quantitatively study how the changes in the sediment discharge in the study area responded to soil erosion control from 1956 to 2016. The three main objectives of this study are as follows: (1) to clarify the changes in the distribution pattern of the sediment sources in the Yellow River over the past 60 years; (2) to identify the contributions of the different tributaries in the main sediment producing areas of the Yellow River to the changes in the sediment discharge; and (3) to reveal the response relationship between the changes in the sediment discharge and the soil erosion control measures and to explain the influence of soil erosion control on the changes in the sediment discharge of the Yellow River.

2. Study area and methods

2.1. Overview of the study area

The increased sediment in the Toudaoguai-Tongguan section of the middle reaches of the Yellow River accounts for 90% of the total sediment in the upper and middle reaches of the Yellow River. This section is the main sand producing area on the Loess Plateau and is the main sediment source of the Yellow River (Xu et al., 2007; Zhao et al., 2017). In order to study the spatial variations in the sediment sources of the Yellow River using four hydrological stations on the trunk stream in the middle reaches of the Yellow River (i.e., the Toudaoguai Hydrological Station, the Wubao Hydrological Station, the Longmen Hydrological Station, and the Tongguan Hydrological Station) as the critical measuring points, the Toudaoguai-Tongguan Section was further divided into the Toudaoguai-Wubao Section, the Wubao-Longmen Section, and the Longmen-Tongguan Section, which mainly include the Weihe River, the Beiluo River, and the Fenhe River. A total of 24 primary tributaries of the Yellow River were selected as the research objects in these three sections. The spatial distribution and detailed information on the studied basins are shown in Fig. 1 and Table 1. The study area covers a total area of 291,000 km^2, of which the soil erosion area accounts for 207,000 km^2.

The Toudaoguai-Tongguan Section is located in the semi-arid and semi-humid transition zone in China, in which the soil is loose, the terrain is broken, the ravines and gullies crisscross, the precipitation is concentrated and mostly occurs in the form of heavy rain, and the local erosion modulus reaches 20,000 t/km^2 per year (Xin et al., 2011). Since the 1970s, the Toudaoguai-Tongguan Section has been a key area for controlling soil erosion on the Loess Plateau, and a series of ecological soil and water conservation projects have been successively implemented in this area. As of 2015, the total area under soil and water conservation measures in the study area reached 107,900 km^2. The

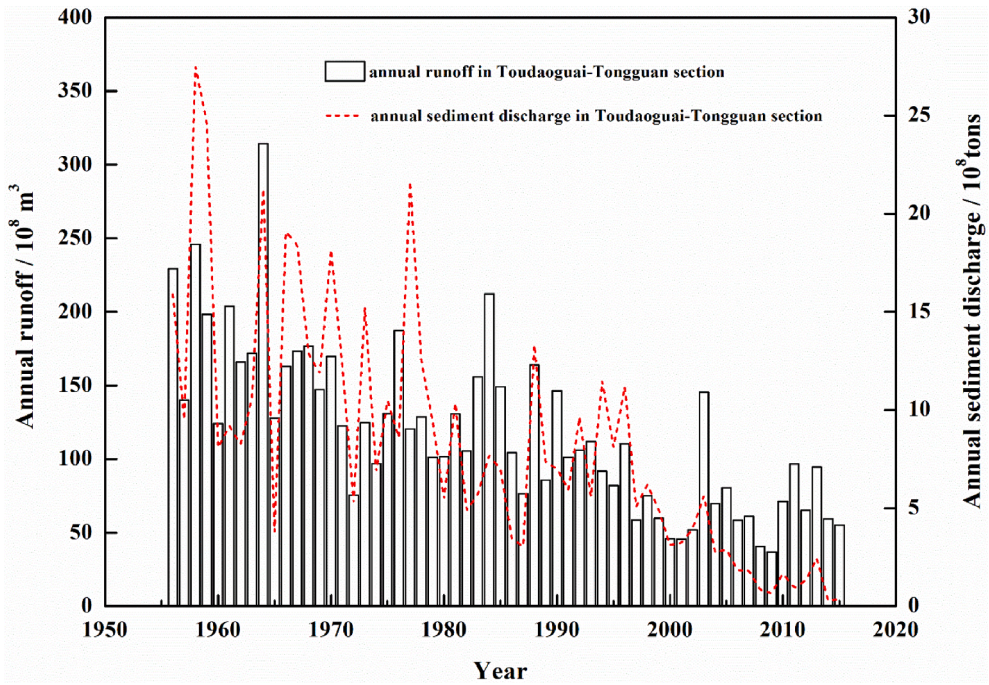


Fig. 2. Interannual variation in the runoff and sediment discharge in the Toudaoguai-Tongguan section.

continuous implementation of soil erosion control projects has played an important role in reducing the sediment flowing into the Yellow River (Wang et al., 2020).

2.2. Data sources

A national network of gauge stations was established throughout the Middle Yellow River Basin in the 1950s to measure the river stage, discharge, and suspended sediment concentration (SSC). We collected time series data for the daily flow and suspended sediment concentration, which were published by the Yellow River Conservancy Committee from 1950s to 2016 for 29 hydrometric stations. The daily suspended sediment load can be calculated as a product of daily flow and the SSC. The monthly and annual data were obtained using the same method. Among these 29 hydrometric stations, 4 stations are located on the mainstream of the middle reaches of the Yellow River, including Toudaoguai, Wubao, Longmen, and Tongguan stations, which will be emphasized in this study. In addition, data for areas with soil and water conservation measures were obtained from the Yellow River Conservancy Committee, which consists of data on the areas of terrace, forest, grass, and check dam sites.

2.3. Soil erosion control degree

The degree of soil erosion control (*SED*) refers to the ratio of the area under soil and water conservation measures to the soil erosion area in the study area. The equation for calculating the SED is as follows:

$$SED = SWA/SLA. \tag{1}$$

where *SWA* is the area under soil and water conservation measures in the basin (ha); and *SLA* is the soil erosion area in the basin (ha).

2.4. Analysis of the trends

The nonparametric Sen's slope and the nonparametric Mann-Kendall test (Hamed, 2009) were used to estimate the decadal trends of the annual runoff and sediment discharge. The index denotes the monotonic trend's magnitude, which was proposed by Sen (1968) and extended by Hirsch et al. (1982) as follows:

$$\beta = \text{Median}\left(\frac{X_j - Y_i}{j - i}\right), 1 < i < j < n \tag{2}$$

where x_i and x_j are the sequential values at time i and j, respectively; and β is the median slope of all of the combinations of the record pairs for the entire data series. A positive value of β suggests an increasing trend, and vice versa.

2.5. Double mass curve

Soil and water conservation-sediment double mass curve (DMC) analysis provides a visual representation of the consistency of the soil and water conservation (SWC) and the sediment data (Grimaldi et al., 2015). The DMC will be a straight line if the two variables are proportional, and the slope of this line is the ratio between the two variables. Changes in the gradient of the curve may indicate that human activities have a significant impact on the sediment changes (Mu et al., 2014). In this study, the DMC between the SWC and sediment data was applied to analyze the impact of SWC on sediment discharge in the study areas. It was also used as an auxiliary confirmation of the change points when the sediment reduction benefits of the soil and water conservation measures became weak.

2.6. Marginal benefit analysis

From the perspective of economics, maximizing the benefits is the basic principle of achieving resource allocation, the basis of which is the theory of diminishing marginal benefits, i.e., under the condition of a constant technological level, if the input of a certain element is continuously increased while the inputs of other elements remain constant, the marginal benefit of this element will diminish (Connor, 2008; Yu and Shang, 2016). With limited financial resources, determining a way to maximize the marginal benefits of soil erosion control in order to achieve better sediment reduction results is a core concern of decision makers in river basin management (Wang et al., 2020). For this reason, the marginal sediment reduction benefits (M) of the soil and water conservation measures implemented in the study area were analyzed

Table 2
Interannual variation in the sediment discharge of the trunk stream in the Toudaoguai-Tongguan section.

Hydrological station	Parameter name	Test Z	Significance test	Average change rate	Break year
Toudaoguai	Annual runoff	−4.30[a)]	***[b)]	−1.94	1986
	Annual sediment discharge	−5.87	***	−0.025	1985
Wubao	Annual runoff	−3.91	***	−2.156	1986
	Annual sediment discharge	−7.05	***	−0.123	2000
Longmen	Annual runoff	−5.14	***	−3.12	1986
	Annual sediment discharge	−7.11	***	−0.22	1999
Tongguan	Annual runoff	−6.10	***	−4.12	1985
	Annual sediment discharge	−7.40	***	−0.25	2000

a) A negative sign indicates decreasing trend.
b) Significant at $P = 0.001$.

using the economic marginal benefit theory. It was assumed that each additional unit of cost per area under soil and water conservation measures generates a corresponding sediment reduction benefit, while the continuous increase in soil and water conservation measures reduced the marginal benefits M. M was calculated as follows:

$$M = \triangle S / \triangle SWM. \quad (3)$$

where $\triangle S$ is the average annual change in the sediment discharge (100 Mt/a); and $\triangle SWM$ is the change in the area under soil and water conservation measures in the basin (km^2/a).

3. Results

3.1. Interannual variation in sediment discharge in the Toudaoguai-Tongguan Section

Through trend analysis of the annual runoff and sediment discharge in the Toudaoguai-Tongguan Section from 1956 to 2016 (Fig. 2), we found that both the annual runoff and the sediment discharge in the main sediment producing area in the middle reaches of the Yellow River significantly decreased over the past 60 years ($P < 0.001$). As can be seen from Table 2, the annual runoff and sediment discharge data measured at the four hydrological stations (i.e., the Toudaoguai Hydrological Station, the Wubao Hydrological Station, the Longmen Hydrological Station, and the Tongguan Hydrological Station) exhibit a significant decreasing trend under different scenarios ($P < 0.001$), and one inflection point was identified in 2000. Further analysis (Fig. 3) shows that the average annual runoff and sediment discharge in the Toudaoguai-Tongguan Section were still increasing downstream, but the rate of increase had decreased significantly. The slope of the fitted line of the changes in sediment discharge decreased from 5.18 in 1950s to 0.46 in the 2010s, with the reduction amplitude of the former being larger than that of the latter.

3.2. Variation in the sediment source in the Toudaoguai-Tongguan Section

Due to the decrease in the sediment discharge in the study area in 2000, the study period was divided into two stages, i.e., from 1956 to 2000 and from 2000 to 2016, for the comparative analysis of the sediment sources (Fig. 4). The total sediment discharge in the Tongguan Station decreased drastically (by 79.2%) from 1.1505 Gt during 1956–2000 to 239.3 Mt during 2001–2016. The sediment discharge in

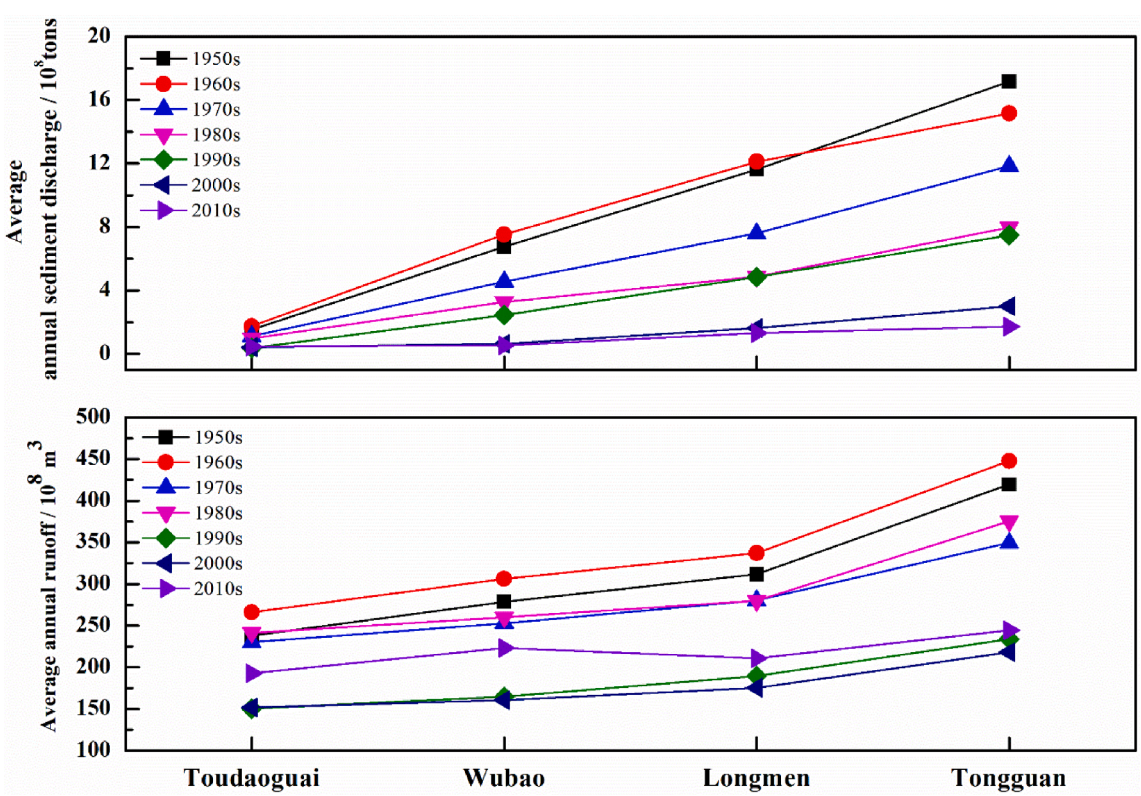


Fig. 3. Variation in the sediment discharge of the main trunk streams in the Toudaoguai-Tongguan section during different time periods.

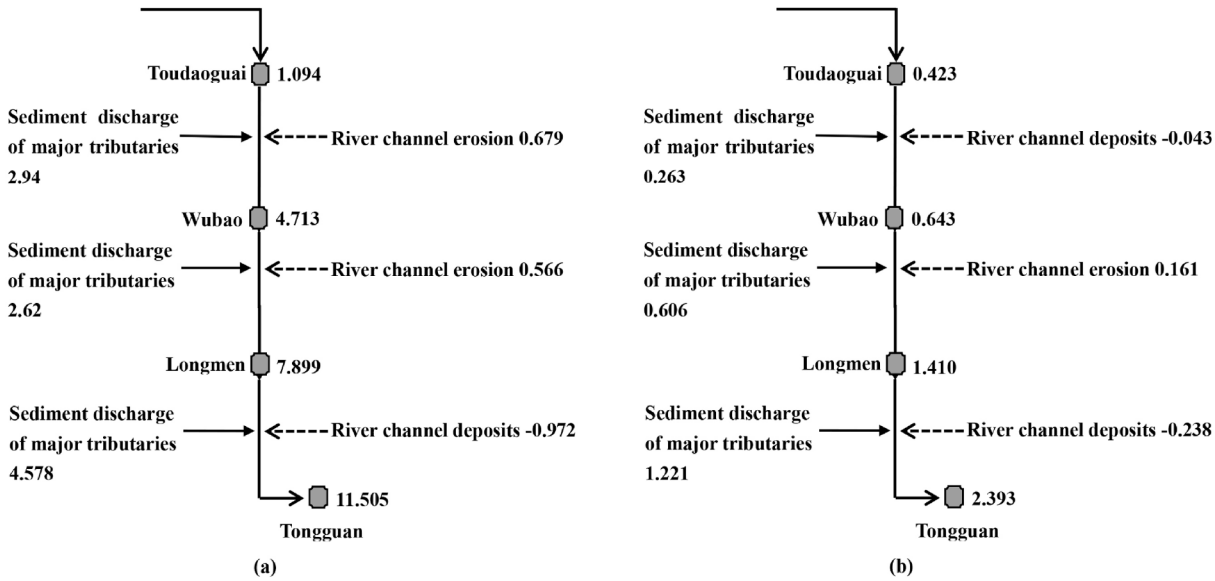


Fig. 4. Spatial distribution of the sediment sources in the Toudaoguai-Tongguan section during period of 1950–2000 (a) and 2001–2016 (b), respectively.

Table 3
Changes in the average annual sediment discharge of the trunk stream of the Yellow River in the Toudaoguai-Tongguan section from 1956 to 2016.[a)]

Section	1956–2000	2001–2016
Toudaoguai-Wubao	+0.313	−0.062
Wubao-Longmen	+0.566	+0.161
Longmen-Tongguan	−0.972	−0.238

[a)] A positive sign indicates river channel deposition and a negative sign indicates river channel erosion.

the Toudaoguai-Tongguan Section decreased sharply (by 81.1%) from 1041.1 Mt during 1956–2000 to 197 Mt during 2001–2016.

As for the composition of the sediment sources in the Toudaoguai-Tongguan Section, from 1956 to 2000, the amount of sediment produced in the areas of the primary tributaries was 1050.4 Mt, and the amount of sediment deposited in the river channels reached 9.3 Mt. From 2001 to 2006, the amount of sediment produced in the areas of the primary tributaries was 210.9 Mt, and the amount of sediment deposited in the river channels reached 13.9 Mt. Generally speaking, from 1956 to 2016, the sediment in the Toudaoguai-Tongguan Section was primarily deposited. Specifically, from 1956 to 2000, the sediment in the Toudaoguai-Longmen Section was mainly scoured, while that in the Longmen-Tongguan Section was mainly silted (see Table 3).

In terms of the spatial distribution of the sediment in the Toudaoguai-Tongguan Section, from 1956 to 2000, the amounts of sediment produced in the Toudaoguai-Wubao Section, the Wubao-Longmen Section, and the Longmen-Tongguan Section contributed 34.76%, 30.60%, and 34.64%, respectively, to the regional sediment production, whereas from 2001 to 2016, their contribution rates reached 11.17%, 38.93%, and 49.9%, respectively. Thus, the spatial source of the sediment in the middle reaches of the Yellow River changed significantly, with the main sediment source changing from the Toudaoguai-Wubao Section to the Longmen-Tongguan Section. This is also related to the change in the way in which sediment is formed in the trunk stream in this section.

3.3. Spatial-temporal variation in the sediment discharge in the areas of main tributaries in the Toudaoguai-Tongguan Section

As can be seen from Fig. 5, during the early period of large-scale soil erosion control (1956–1970), the intensity of the sediment discharge in the main sediment producing area in the middle reaches of the Yellow River was characterized by significant spatial heterogeneity, with intense sediment discharge in the northwest and relatively weak sediment discharge in the east and southwest. The Wuding River, the Kuye River, and the Huangfu River had the strongest sediment discharge intensities, with a sediment discharge module exceeding 20,000 $t \cdot km^{-2} \cdot yr^{-1}$, making it the world's most famous soil erosion area and the concentrated source of the coarse sediment in the Yellow River. Through comparative analysis of the average sediment discharge modulus of each tributary during 2001–2016 and during 1956–1970, we found specific changes in the intensity of the sediment discharge in the middle reaches of the Yellow River. The overall intensity of the sediment discharge decreased sharply, and the most significant decreased occurred in the Toudaoguai-Wubao Section in the middle reaches of the Yellow River. The average sediment discharge of each tributary decreased by more than 90%, while the average decrease in the Longmen-Tongguan Section was 84%.

3.4. Contribution of the main tributaries to the sharp decrease in the sediment discharge in the Toudaoguai-Tongguan Section

As can be seen from Table 4, the average annual sediment discharges of the 24 primary tributaries in the middle reaches of the Yellow River significantly decreased, with a reduction ratio of 62.6–98.61% and an average of 85.61%. The average annual sediment discharge of the tributaries in the Toudaoguai-Wubao Section decreased by 89.97%, while those of the tributaries in the Wubao-Longmen and Longmen-Tongguan sections decreased by 79.49% and 83.03%, respectively. Among the primary tributaries, the changes in the average annual sediment discharges of the Weihe River, the Wuding River, and the Kuye River contributed the most to the decrease in sediment discharge in the middle reaches, i.e., 29.63%, 11.75%, and 11.23%, respectively, reaching 52.61% cumulatively. The contribution rates of the remaining tributaries were all less than 10%.

4. Discussion

The river sediment mainly comes from surface erosion, gully erosion, and scouring of the river channels, while the soil erosion resulting from surface erosion by surface runoff due to heavy precipitation is the main source of river sediment (Fan and Cai, 2004; Haddadchi et al., 2016). Studies have shown that the erosion intensity is related to precipitation,

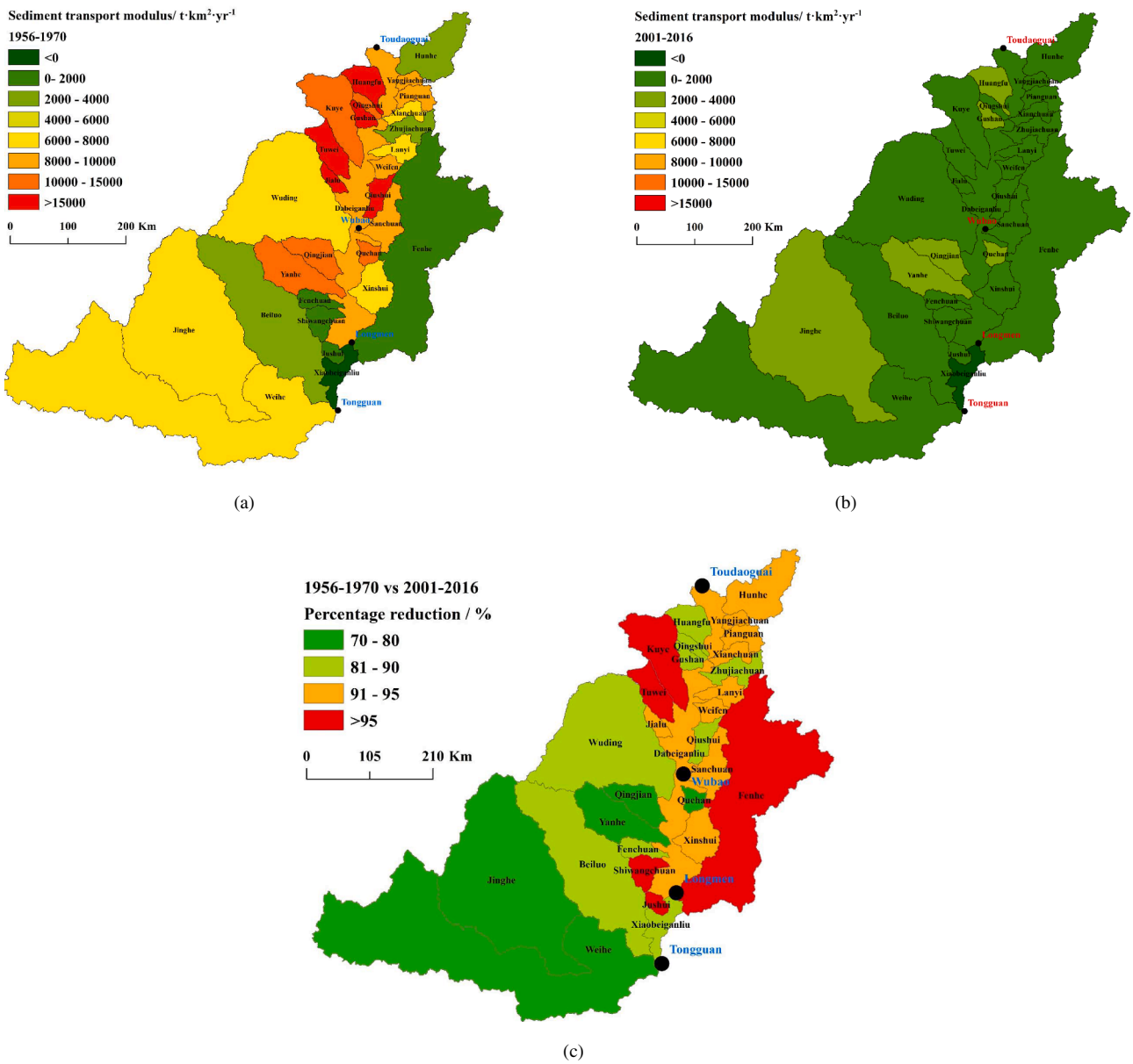


Fig. 5. Spatiotemporal variation of sediment transport modulus in the middle Yellow River during 1956 s–2016 s. (a) The annual sediment transport modulus in the 1950 s–1970 s (t·km^{-2}·yr^{-1}); (b) the sediment transport modulus in the 2000 s–2016 s (t·km^{-2}·yr^{-1}); (c) percent change in sediment transport modulus in 2000 s–2016 s relative to that in the 1956 s–2000 s. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

soil type, topography, and land cover changes (Zhao et al., 2012). However, present studies indicate that all of the annual precipitation and different classes of precipitation had no significant changing trends on the whole in the middle reaches of the Yellow River from 1966 to 2016 (He et al., 2015; Wang et al., 2017; Dang et al., 2018). Therefore, for a certain area, without periodic changes in precipitation, the erosion and sediment yield are mainly restricted by topographic factors and underlying conditions (Zhang et al., 2015). In fact, in the past 50 years, large-scale soil and water conservation and ecological construction have caused profound changes in the land use structure on the Loess Plateau. The amounts of forest and grassland have increased significantly, mitigating soil erosion. As described in detail previously, due to the soil erosion control, the changes in the topography and the underlying surface have undoubtedly become the key factors driving the changes of sediment discharge in the middle reaches of Yellow River Basin, with an average contribution rate of more than 85% (Gao et al., 2016; Gu et al., 2018; Zhao et al., 2018). Therefore, based on the results of previous studies and assuming that precipitation did not have a significant effect on the changes in sediment discharge in this basin, we further analyzed the influence of soil erosion control on the sediment discharge in the study area.

4.1. Changes in the area under soil and water conservation measures

Large scale soil erosion control was implemented in the middle reaches of the Yellow River in the 1970s (Hu and Zhang, 2020). Fig. 6 shows that from 1956 to 2015, the total area under soil and water conservation measures in the study area increased on a yearly basis. The area under soil and water conservation measures increased at a constant rate from 1970 to 2000, with an average annual increase of 1800 km^2. After 2000, with the implementation of the returning farmland to forests and grasslands project, the soil erosion control was further strengthened, and the area under soil and water conservation measures increased by an average of 2800 km^2 every year. According to the statistical results

Table 4
Changes in the average annual sediment discharge of the main primary tributaries in the Toudaoguai-Tongguan section from 1956 to 2016.

Section	Tributary/trunk stream	1956–2000/million tons	2001–2016/million tons	Change/%	Contribution rate to sediment reduction/%
Toudaoguai-Wubao	Huangfu	0.48	0.075	84.40	4.80
	Qingshui	0.37	0.019	94.92	4.12
	Gushanchuan	0.22	0.033	84.60	2.16
	Kuye	0.98	0.028	97.13	11.23
	Tuwei	0.20	0.015	92.61	2.23
	Jialu	0.17	0.016	90.61	1.81
	Qiushui	0.19	0.014	92.67	2.10
	Fenwei	0.11	0.012	88.79	1.13
	Lanyi	0.08	0.008	89.87	0.84
	Zhujiachuan	0.14	0.013	90.44	1.46
	Xianchuan	0.12	0.009	92.62	1.34
	Pianguan	0.11	0.009	91.59	1.16
	Huhe	0.16	0.032	79.35	1.46
	Dabei main stream	0.88	0.099	88.74	9.24
Wubao-Longmen	Wuding	1.25	0.260	79.24	11.75
	Qingjian	0.37	0.139	62.63	2.76
	Yanhe	0.48	0.123	74.21	4.20
	Fenchuan	0.04	0.006	83.33	0.36
	Shiwangchuan	0.03	0.001	96.55	0.33
	Xishui	0.17	0.021	87.50	1.74
	Quchan	0.09	0.032	65.05	0.70
	Sanchuan	0.19	0.024	87.42	2.01
Longmen-Tongguan	Weihe	3.56	1.059	70.25	29.63
	Beiluo	0.81	0.159	80.23	7.66
	Fenhe	0.21	0.003	98.61	2.48
	Xiaobei main stream	−0.97	−0.238	75.51	−8.70

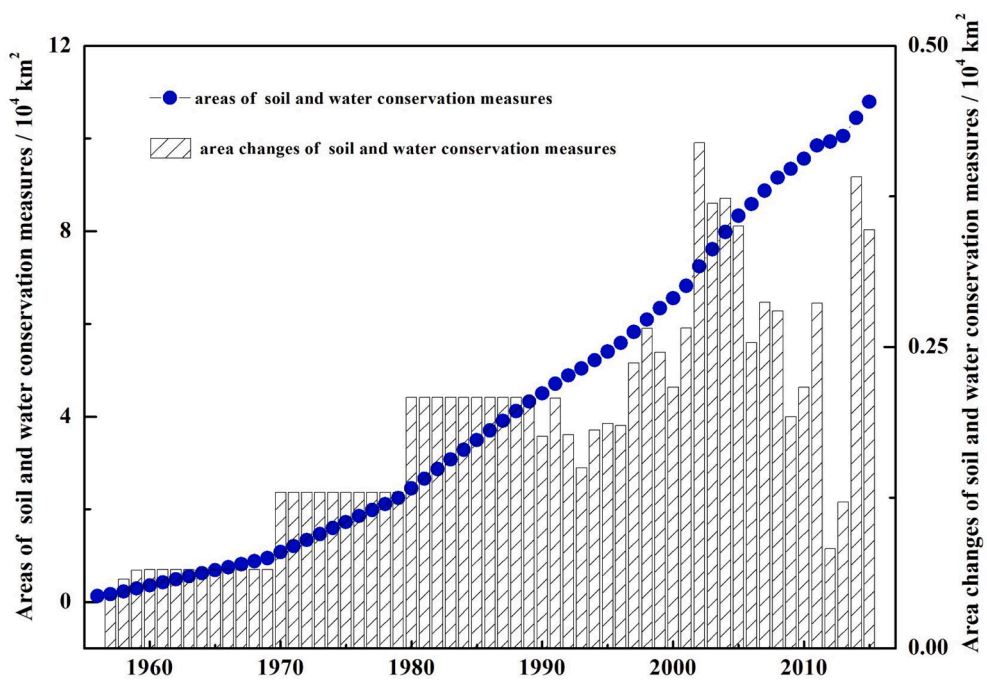


Fig. 6. Interannual variation in the area under soil and water conservation measures in the study area from 1956 to 2015.

for the different tributaries in the study area, as of 2015, the total area under soil and water conservation measures in the study area reached 107,900 km^2, of which the area of terraces was 24,900 km^2, the area of the forests and grassland was 71,800 km^2, the area of dams was 837.1 km^2, and the closed control area was 10,400 km^2.

4.2. Influence of the soil and water conservation measures on sediment discharge

The double mass curve method was used to statistically analyze the area under soil and water conservation measures and the cumulative annual sediment discharge in the study area. As can be seen from Fig. 7, there is a significant exponential relationship between the area under soil and water conservation measures and the cumulative annual sediment discharge in the study area at a 99% confidence level, and the correlation coefficient between the two reaches 0.99. This indicates that the increase in the area under soil and water conservation measures in the study area significantly influenced the sediment discharge. Specifically, at the beginning of the conservation project (1956–1980), due to the small area under soil and water conservation measures in the study area, the cumulative annual sediment discharge rapidly increased. As the area under soil and water conservation measures continued to

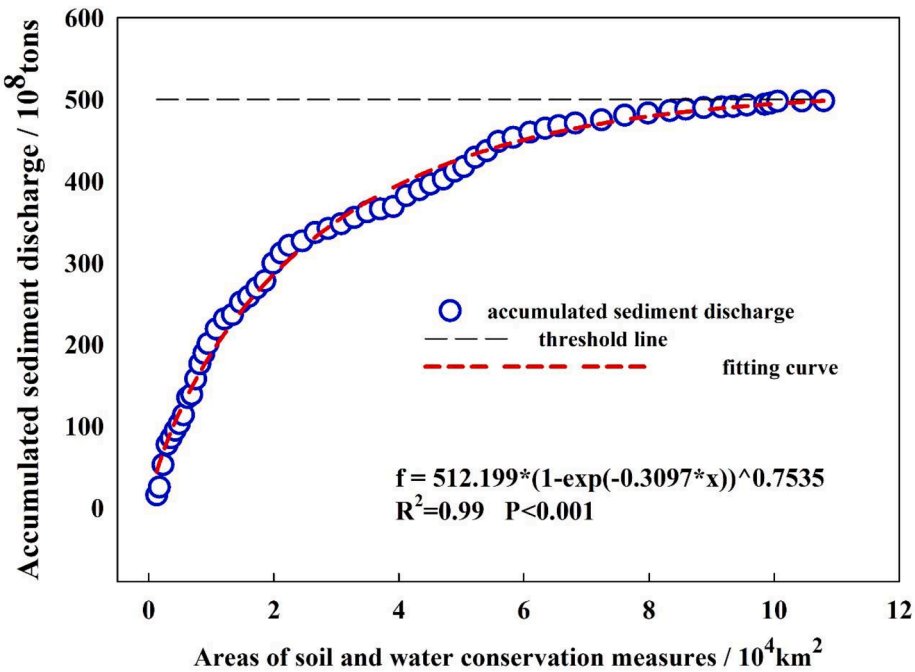


Fig. 7. Response relationship between the cumulative sediment discharge and the area under soil and water conservation measures.

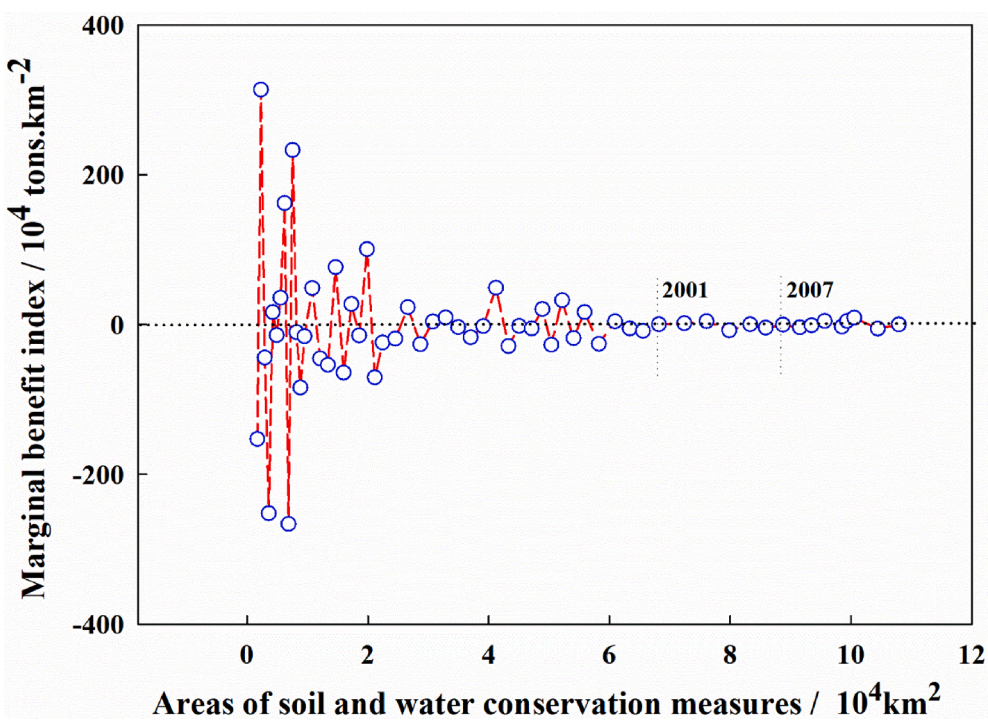


Fig. 8. Marginal benefit of the soil and water conservation measures to sediment reduction in the Toudaoguai-Tongguan section.

increase, the soil and water conservation measures continued to play their role in reducing the flow and sediment, and the increase in the cumulative annual sediment discharge in the study area slowed down significantly, with the cumulative sediment discharge approaching a constant value of 50 Gt. Specifically, 50 Gt is the maximum sediment reduction capacity of the current soil and water conservation measures under the current level of soil erosion control.

4.3. Marginal sediment reduction benefits of soil and water conservation measures

As is shown in Fig. 8, the marginal sediment reduction benefits of the soil and water conservation measures in the study area reached a critical point in 2000, corresponding to a degree of soil erosion management of 32% (when the area under soil erosion control reached 65,500 km^2). Prior to 2000, the soil and water conservation measures had a large marginal sediment reduction benefit, and the implementation of soil and water conservation measures greatly affected the changes in the

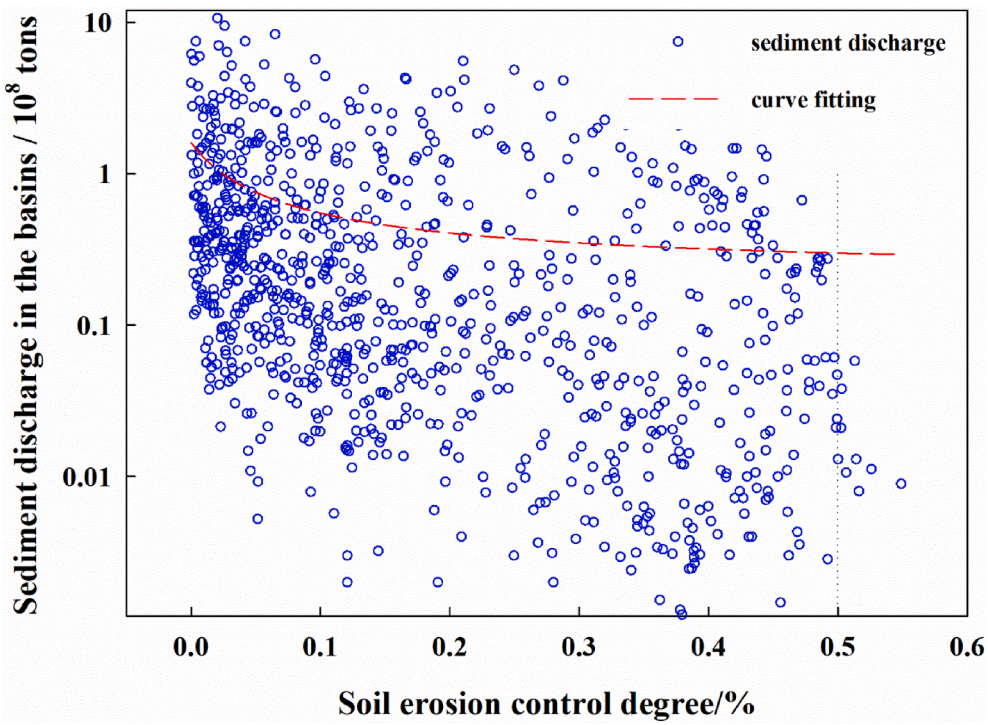


Fig. 9. Correlation between sediment discharge and the degree of soil erosion control in a river basin.

sediment discharge in the study area, which fluctuating around zero. However, after 2000, as the area of soil and water conservation measures increased, the degree of soil erosion management gradually increased from 32% to greater than 50%, while the marginal benefit curve flattened, indicating that the decrease in the annual sediment transport per unit area caused by the soil and water conservation measures gradually decreased, and the marginal benefits of the soil and water conservation measures gradually decreased, eventually becoming constant.

In addition, taking the main first-order tributaries with a large contribution rate (greater than 4%) to the sediment reduction in the study area as the research objects, a statistical analysis of the changes in the annual sediment transports in multiple basins due to the changes in the degree of soil and water erosion management measures in these basins was conducted. As is shown in Fig. 9, there is a statistically significant negative correlation between the sediment discharge and the degree of soil erosion control in the river basin. When the degree of soil erosion management in a given basin reached 35%, the annual sediment transport curve of that basin began to flatten. When the degree of soil erosion management exceeded 50%, the sediment transport in the basins reached a low level and stabilized. The above analysis shows that on both the regional scale and the basin scale, after 2010, under the current degree of soil erosion management, the sediment transport in these basins remained at a historically low level and remained steady. The relevant research results are consistent with those of Wang et al. (2020) and Mu et al. (2020).

5. Conclusions

The spatial distribution and temporal variations in the river sediment reflect the spatial–temporal characteristics of and variations in the soil erosion. The middle reaches of the Yellow River is the region with the most severe soil erosion in the world, and the sediment discharge in the middle reaches directly determines the amount of sediment in the Yellow River. The 24 primary tributaries selected in this study included almost all of the primary tributaries with hydrological stations in the middle reaches of the Yellow River. In this study, we systematically analyzed the dynamic response relationship between the changes in sediment discharge and the soil erosion control measures in the main sediment producing area of the Yellow River. The results show that there is a significant correlation between the soil erosion control and the drastic reduction in the sediment discharge of the Yellow River, and there is a critical threshold between the two. Specifically, when the overall degree of regional soil erosion control reaches 32%, the marginal sediment reduction benefits of the soil and water conservation measures become smaller; and when the degree of soil erosion control of the main tributaries exceeds 50%, the sediment discharge in the river basin drops to a low level. Currently, the degree of soil erosion control of the tributaries of the middle reaches of the Yellow River ranges from 35% to 55%.

Based on the above research conclusions, from the perspective of reducing sediment discharge, for river basins with degrees of soil erosion control ranging from 35% to 50%, strengthening the areas under soil and water conservation measures should be the key direction of soil erosion management in the future. For river basins with degrees of soil erosion control exceeding 50%, continuing to carry out large-scale soil erosion control will have a very limited influence on reducing the sediment discharge in the river, and it is important to enhance the post-construction maintenance of existing soil and water conservation measures, e.g., safety measures and the reinforcement of silt dams, renovation and enhancement of inefficient plantation structures, maintenance of old terraces, and the supply of supporting drainage facilities, so as to guarantee the continuous and effective benefits of the soil and water conservation measures already in place.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was financially supported by the National Key

Research and Development Program of China (No. 2016YFC0402407), the National Nature Science Foundation of China (NO. 51979290, 51879281), the special research project of the China Institute of Water Resources and Hydropower Research (SE0145B132020), the independent research project of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (NO. SKL2020TS10). We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

References

Benn, P.C., Erskine, W.D., 1994. Complex channel response to flow regulation: Cudgegong River below Windamere Dam. Australia. Appl. Geogr. 14 (2), 153–168.
Brauer, A., Endres, C., Günter, C., et al., 1999. High resolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar, Germany. Quat. Sci. Rev. 18 (3), 321–329.
Chen, J.R., Ren, L., Ren, S., 2019. An analysis of water and sediment contribution rate in middle reaches of the Yellow River. Zhongguo Nongcun Shuili Shuidian 11, 1–4.
Connor, J., 2008. The economics of time delayed salinity impact management in the River Murray. Water Resour. Res. 44 (3), 393–408.
Dang, S., Liu, X., Li, X., et al., 2018. Changes in Different Classes of Precipitation and the Impacts on Sediment Yield in the Hekouzhen-Longmen Region of the Yellow River Basin, China. Adv. Meteorol. 2018, 1–15.
Fan, H.M., Cai, Q.G., 2004. Research progress on the soil erosion and sediment yield budget in watersheds. Nisha Yanjiu 2, 76–80.
Fu, B., 1989. Soil erosion and its control in the loess plateau of China. Soil Use Manage. 5 (2), 76–82.
Gao, P., Deng, J., Chai, X., et al., 2016. Dynamic sediment discharge in the Hekou-Longmen region of Yellow River and soil and water conservation implications. Sci. Total Environ. 578, 56–66.
Giardino, A., Schrijvershof, R., Nederhoff, C.M., et al., 2018. A quantitative assessment of human interventions and climate change on the West African sediment budget. Ocean Coast. Manage. 156, 249–265.
Grimaldi, S., Angeluccetti, I., Coviello, V., et al., 2015. Cost-effectiveness of soil and water conservation measures on the catchment sediment budget–the Laaba watershed case study, Burkina Faso. Land Degrad. Dev. 26 (7), 737–747.
Gu, C., Mu, X., Gao, P., et al., 2018. Changes in run-off and sediment load in the three parts of the Yellow River basin, in response to climate change and human activities. Hydrol. Process. 33 (4), 585–601.
Haddadchi, A., Olley, J., Pietsch, T., 2016. Using LM-OSL of quartz to distinguish sediments derived from surface-soil and channel erosion. Hydrol. Process. 30 (4), 637–647.
Hamed, K.H., 2009. Exact distribution of the Mann-Kendall trend test statistic for persistent data. J. Hydrol. 365 (1–2), 86–94.
He, Y., Mu, X., Gao, P., et al., 2015. Spatial variability and periodicity of precipitation in the middle reaches of the Yellow River, China. Adv. Meteorol. 2016, 1–9.
Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18 (1), 107–121.
Hu, C., Chen, J., 2014. New exploration on water-sediment variation of river and its harnessing. Shuili Shuidian Jishu 45 (1), 11–15.
Hu, C., Zhang, X., 2020. Loess Plateau soil erosion governance and runoff-sediment variation of Yellow River. Shuili Shuidian Jishu 51 (1), 1–11.
Kang, L., Zhang, S., Wei, Y., et al., 2010. Review of the effects researches of soil and water conservation on sediment reduction in the middle reaches of the Yellow River. Zhongguo Shuitu Baochi Kexue 8 (2), 111–116.
Li, L., Ni, J., Chang, F., et al., 2020. Global trends in water and sediment fluxes of the world's large rivers. Sci. Bull. 65 (1), 62–69.
Liquete, C., Canals, M., Ludwig, W., et al., 2009. Sediment discharge of the rivers of Catalonia, NE Spain, and the influence of human impacts. J. Hydrol. 366 (1–4), 76–88.
Liu, X., Dang, S., Zhang, H., 2016. Possible incoming sediment amount of the Yellow River under the extreme rainfall scenarios in the future. Renmin Huanghe 38 (10), 13–17.
Miao, C., Ni, J., Borthwick, A.G.L., 2010. Recent changes of water discharge and sediment load in the Yellow River basin. China. Prog. Phys. Geogr. 34 (4), 541–561.
Miao, C., Ni, J., Borthwick, A.G.L., et al., 2011. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. Glob. Planet Change 76 (3–4), 196–205.
Mu, X.M., Wang, W.Z., Gao, P., et al., 2014. Progress and discussion on sediment load variation research of the Yellow River. Renmin Huanghe 36 (12), 1–7.
Mu, X., Zhao, G., Gao, P., et al., 2020. Future trend of sediment discharge in Yellow River and its adaptation strategies. Bullet. Soil Water Conserv. 40 (5), 1–11.
Ni, J., Han, P., Wang, G., et al., 1997. Variations of sediment characteristics in the middle reach of Yellow River with respect to regional water and soil conservation: II. benefit analysis of reducing the sediment. Ziran Ziyuan Xuebao 12 (2), 126–131.
Ren, M.E., 1994. Impact of climate change and human activity on flow and sediment of the rivers—the Yellow River (China) example. GeoJournal 33 (4), 443–447.
Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63 (324), 1379–1389.
Vaighan, A.A., Talebbeydokhti, N., Bavani, A.M., 2017. Assessing the impacts of climate and land use change on streamflow, water quality and suspended sediment in the Kor River Basin, Southwest of Iran. Environ. Earth. Sci. 76 (15), 543.
Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Glob Planet Change 39 (1–2), 111–126.
Wang, G., Zhong, D., Wu, B., 2020. Future trend of Yellow River sediment changes. Zhongguo Shuili 1, 9–12.
Wang, H., Gao, J., Wang, H., et al., 2015. Impact of soil and water conservation measures on runoff and sediment environment in Wei River Basin. Nat. Environ. Pollut. Technol. 14 (4), 777–784.
Wang, Q., Wang, M., Fan, X., et al., 2017. Trends of temperature and precipitation extremes in the Loess Plateau Region of China, 1961–2010. Theor. Appl. Climatol. 129 (3), 949–963.
Wang, S., Fu, B., Piao, S., et al., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9 (1), 38–41.
Wu, Y., Chen, J., 2012. Modeling of soil erosion and sediment transport in the East River Basin in southern China. Sci. Total Environ. 441, 159–168.
Xin, Z., Yu, X., Li, Q., et al., 2011. Spatiotemporal variation in rainfall erosivity on the Chinese Loess Plateau during the period 1956–2008. Reg. Environ. Change 11 (1), 149–159.
Xu, J.H., Gao, Y.J., Li, X.Y., et al., 2007. Impact of controlling to sediment-laden and coarse sand area in middle Yellow River on water resource of lower Yellow River. Shuitu Baochi Xuebao 21 (6), 47–50.
Yang, H.F., Yang, S.L., Xu, K.H., et al., 2017. Erosion potential of the Yangtze Delta under sediment starvation and climate change. Sci. Rep. 7, 10535.
Yao, W., 2019. Development opportunity and scientific positioning of soil and water conservation of the Yellow River in the new era. Renmin Huanghe 41 (12), 1–7.
Yao, W., Xu, J., 2013. Impact of human activity and climate change on suspended sediment load: the upper Yellow River, China. Environ. Earth Sci. 70 (3), 1389–1403.
Yu, Z., Shang, S., 2016. Multi-objective optimization method for irrigation scheduling of crop rotation system and its application in North China. Shuili Xuebao 47 (9), 1188–1196.
Zhang, J., Zhang, X., Li, R., et al., 2017. Did streamflow or suspended sediment concentration changes reduce sediment load in the middle reaches of the Yellow River? J. Hydrol. 546, 357–369.
Zhang, S., Chen, D., Chen, L., et al., 2019. Using sediment rating parameters to evaluate the changes in sediment transport regimes in the middle Yellow River basin, China. Hydrol. Process 33 (18), 2481–2497.
Zhang, X., Li, P., Li, Z., et al., 2015. Characteristics of erosion and sediment yield under critical landform in hill-gully area of Loess Plateau. Trans. o CSAE 31 (4), 129–136.
Zhao, G., Kondolf, G.M., Mu, X., et al., 2017. Sediment yield reduction associated with land use changes and check dams in a catchment of the Loess Plateau, China. CATENA 148, 126–137.
Zhao, H., Lu, X., Fan, X., 2012. Current situation of soil erosion and its countermeasures in Tibet. Zhongguo Shuitu Baochi Kexue 10 (3), 120–122.
Zhao, Y., Hu, C., Zhang, X., et al., 2018. Analysis on runoff and sediment regimes and its causes of the Yellow River in recent 70 years. Nongye Gongcheng Xuebao 34 (21), 112–119.